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Duparré

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(54) **SYSTEMS AND METHODS FOR CORRECTING FOR WARPAGE OF A SENSOR ARRAY IN AN ARRAY CAMERA MODULE BY INTRODUCING WARPAGE INTO A FOCAL PLANE OF A LENS STACK ARRAY**

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(58) **Field of Classification Search**

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See application file for complete search history.

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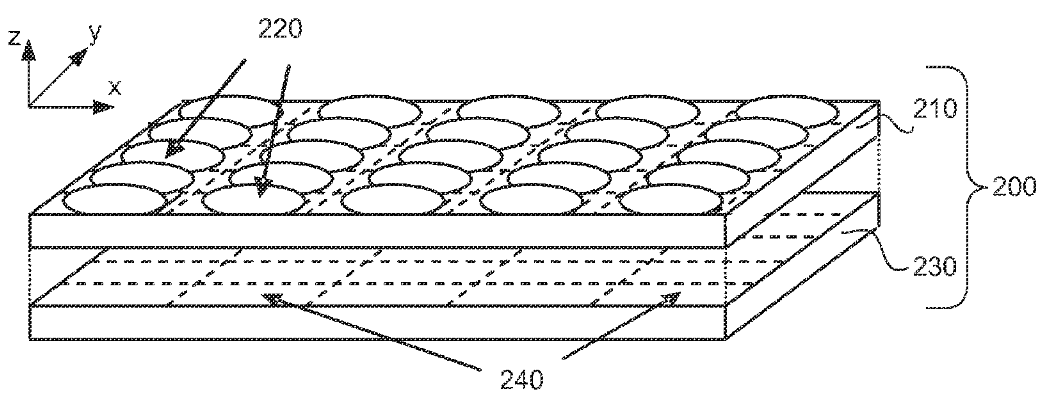
(57) **ABSTRACT**

Systems and methods in accordance with embodiments of the invention provide an array camera module in which warpage is designed into the projection plane of images from a lens stack array to correct for warpage in a sensor of the array camera module. The resulting array camera modules has back focal lengths for each of the lens stacks in the lens stack array that are substantially consistent when placed over a sensor.

18 Claims, 10 Drawing Sheets



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Boye et al., "Comparison of Subpixel Image Registration Algorithms", Proc. of SPIE-IS&T Electronic Imaging, vol. 7246, pp. 72460X-1-72460X-9.

* cited by examiner

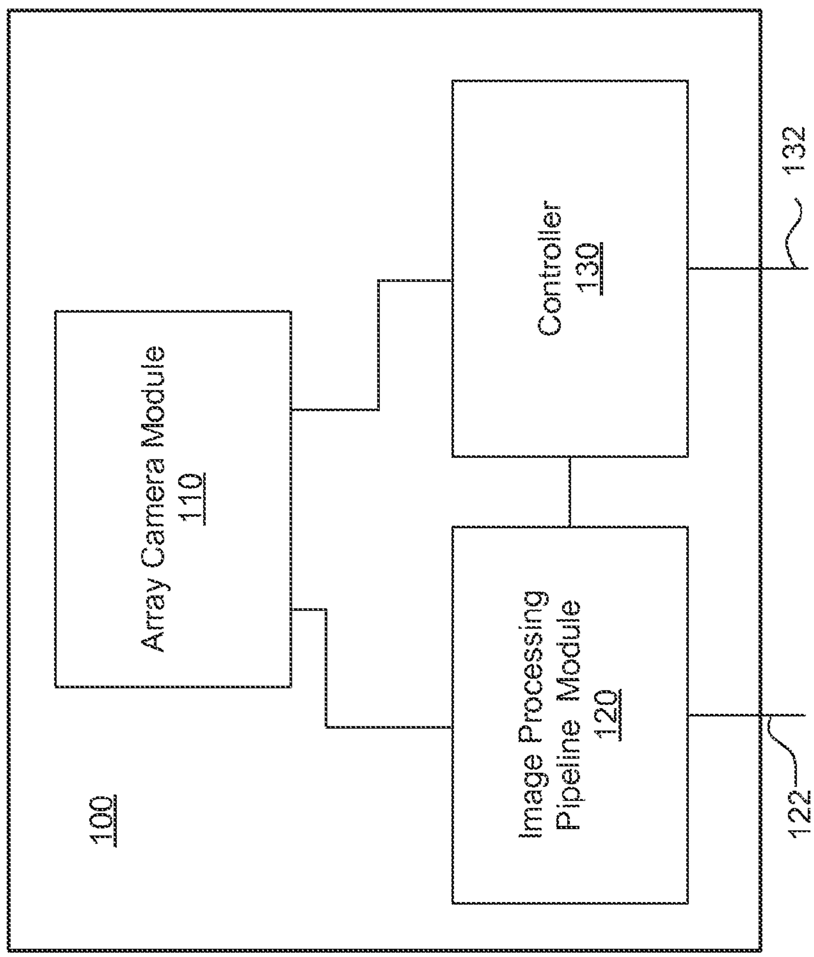

100
Array Camera Module
110
Controller
130
Image Processing
Pipeline Module
120
122
132

FIG. 1

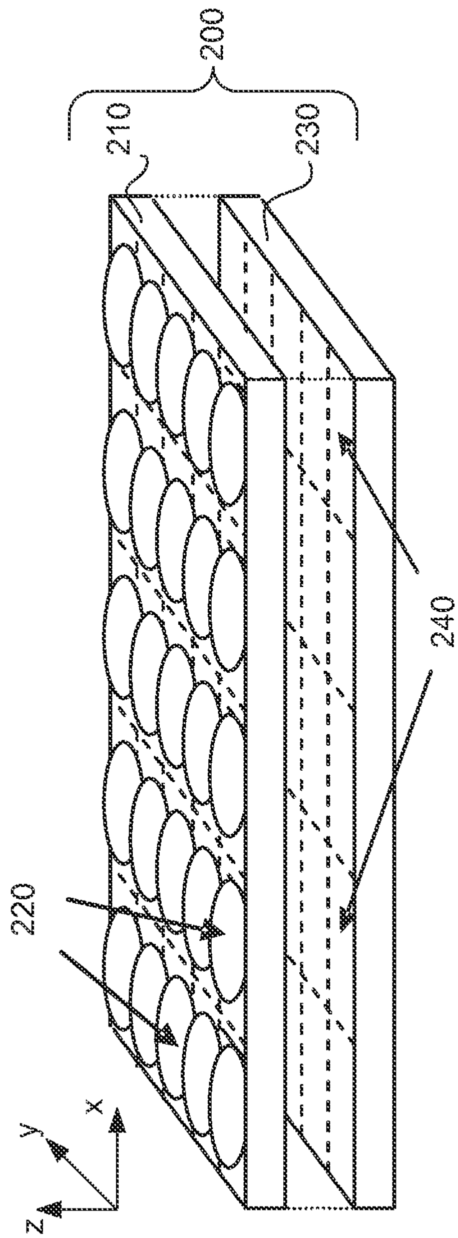


FIG. 2

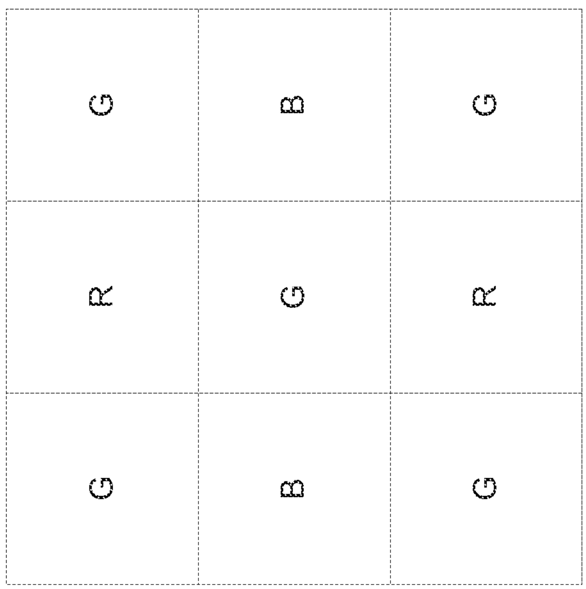


FIG. 3

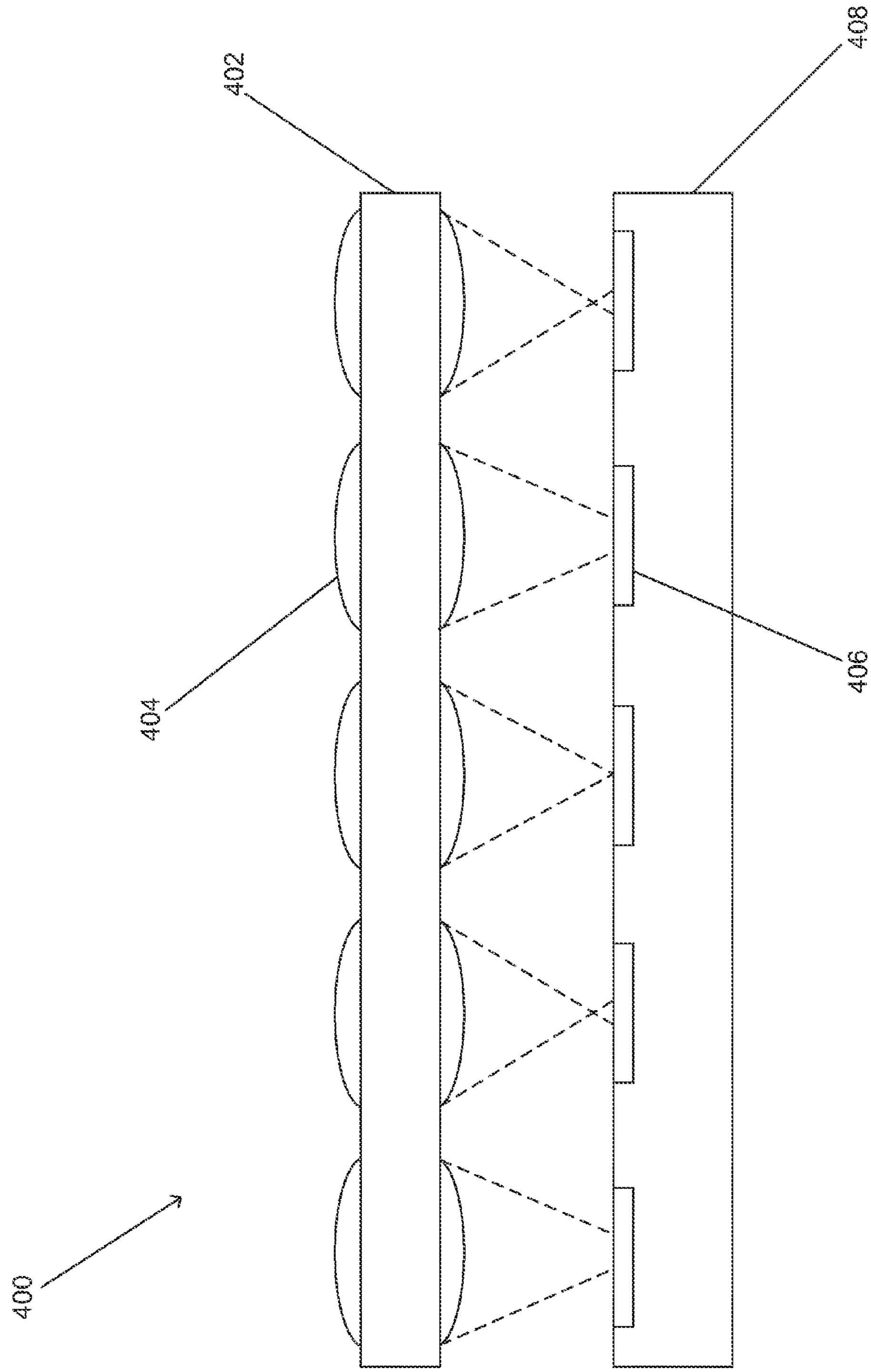


FIG. 4

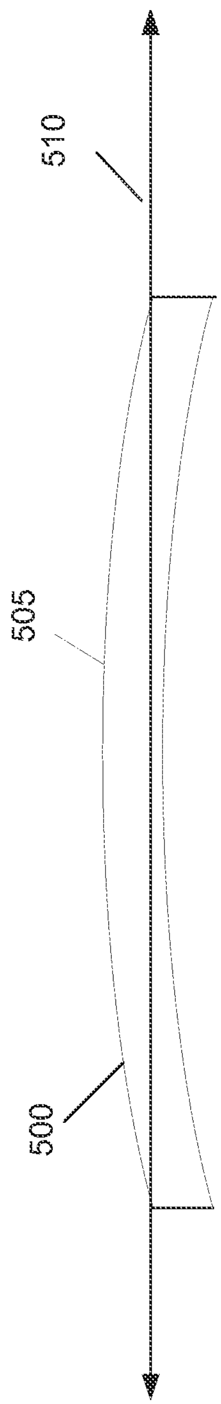


FIG. 5

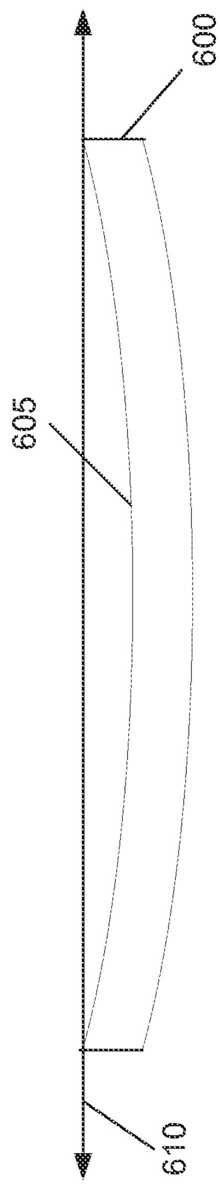


FIG. 6

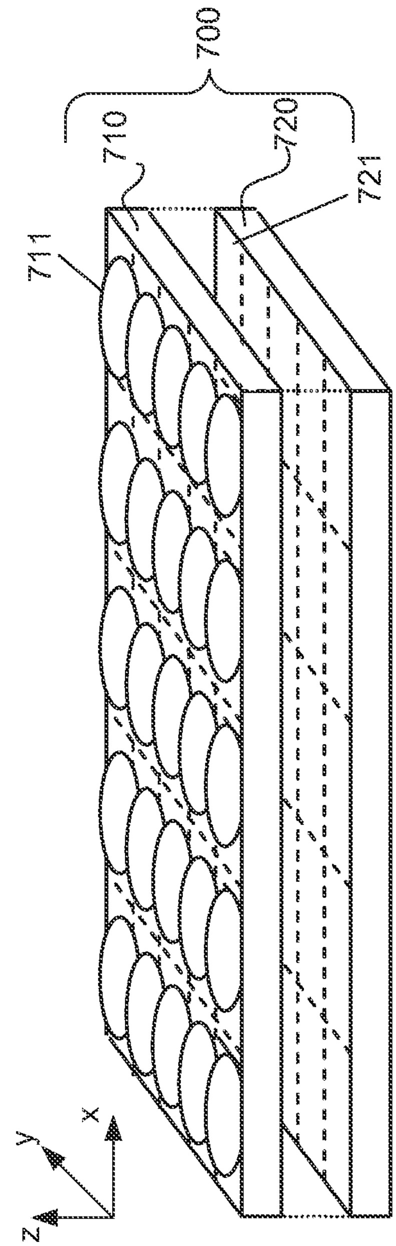


FIG. 7

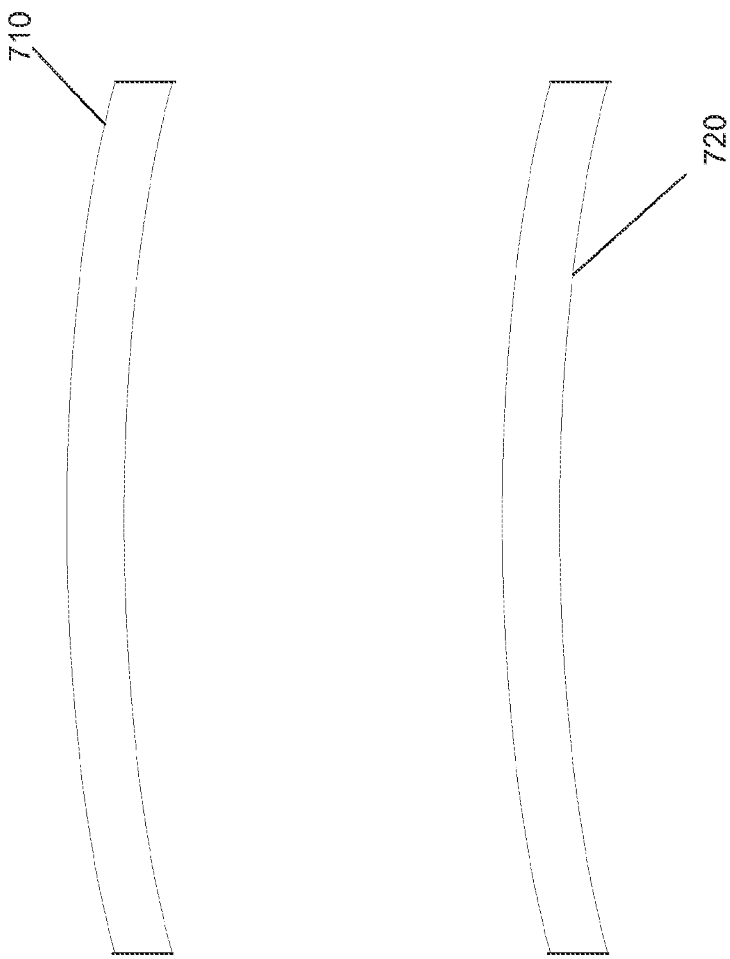
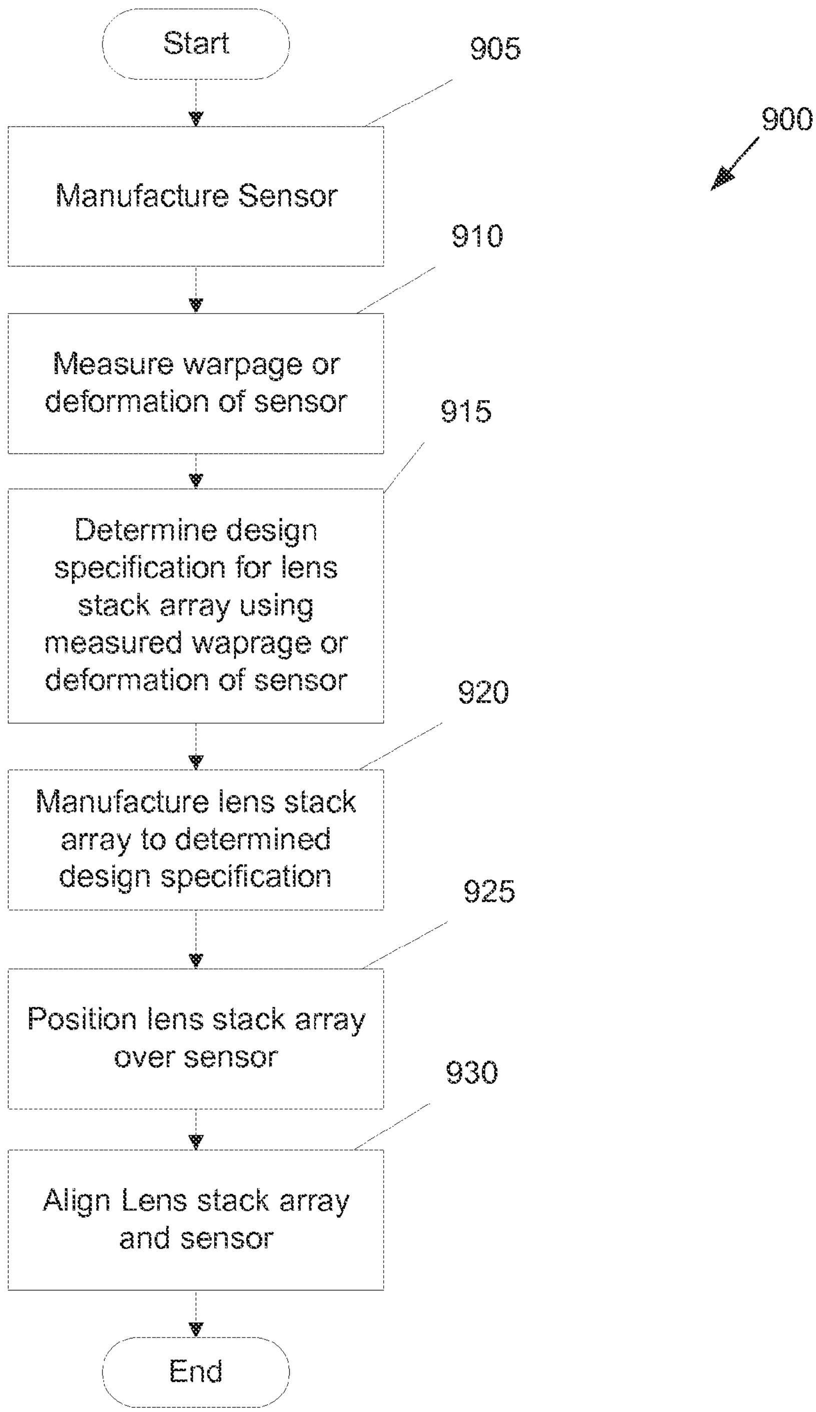
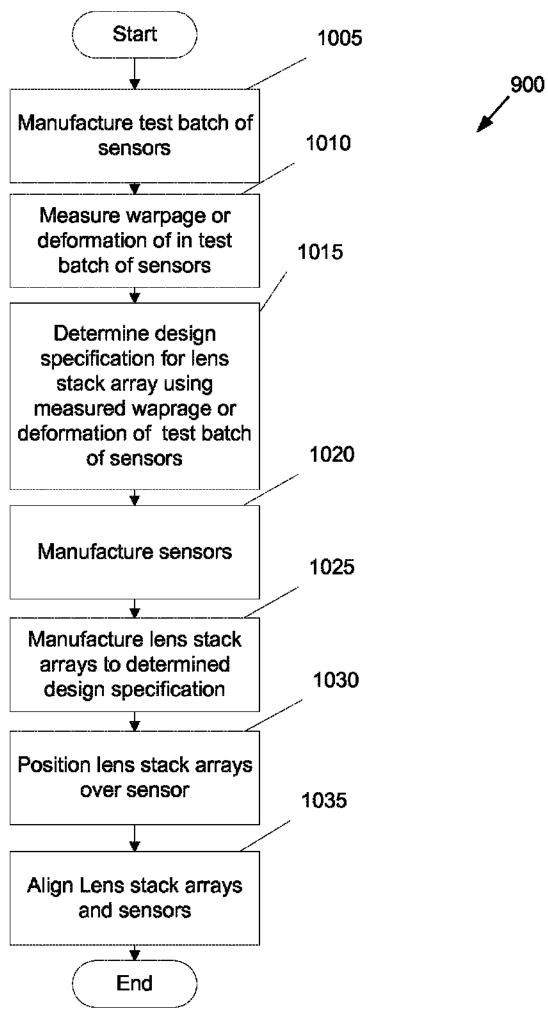


FIG. 8



Start
905
Manufacture Sensor
910
Measure warpage or deformation of sensor
915
Determine design specification for lens stack array using measured waprage or deformation of sensor
920
Manufacture lens stack array to determined design specification
925
Position lens stack array over sensor
930
Align Lens stack array and sensor
End
900

FIG. 9



Start
1005
900
Manufacture test batch of sensors
1010
Measure warpage or deformation of in test batch of sensors
1015
Determine design specification for lens stack array using measured waprage or deformation of test batch of sensors
1020
Manufacture sensors
1025
Manufacture lens stack arrays to determined design specification
1030
Position lens stack arrays over sensor
1035
Align Lens stack arrays and sensors
End

FIG. 10

SYSTEMS AND METHODS FOR CORRECTING FOR WARPAGE OF A SENSOR ARRAY IN AN ARRAY CAMERA MODULE BY INTRODUCING WARPAGE INTO A FOCAL PLANE OF A LENS STACK ARRAY

CROSS-REFERENCE TO RELATED APPLICATION

The present invention claims priority under 35 U.S.C. §119 (e) to U.S. Provisional Patent Application Ser. No. 61/976, 335 entitled "Sensor Array Warpage Compensation by Intentionally Introducing Warpage into the Lens Array", filed Apr. 7, 2014, the disclosure of which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present invention generally relates to reducing the variation of the back focal length of lens in a lens stack array of an array camera module.

BACKGROUND

In response to the constraints placed upon a traditional digital camera based upon the camera obscura, a new class of cameras that can be referred to as array cameras has been proposed. Array cameras are characterized in that they include an imager array, or sensor, that has multiple arrays of pixels, where each pixel array is intended to define a focal plane, and each focal plane has a separate lens stack. Typically, each focal plane includes a plurality of rows of pixels that also forms a plurality of columns of pixels, and each focal plane is contained within a region of the imager that does not contain pixels from another focal plane. An image is typically formed on each focal plane by its respective lens stack. In many instances, the array camera is constructed using an imager array that incorporates multiple focal planes and an optic array of lens stacks.

SUMMARY OF THE INVENTION

An advance in the art is by systems and methods for correcting warpage of a sensor array in an array camera module by introducing warpage into a projection plane of images formed by the lens stack in accordance with at least some embodiments of this invention. In accordance with some embodiments of the invention, an array camera includes an array camera module. The array camera module includes a sensor and a lens stack array. The sensor includes an array of pixels that is subdivided into a sub-arrays of pixels and each of the sub-arrays forms a focal plane. The lens stack array includes a set of lens stacks. Each of lens stacks includes an aperture and forms an image on a focal plane formed by one of the sub-array of pixels on the sensor. The surface of the sensor on which images are formed includes a warpage and a projection plane of images formed by the lens stack array incorporates a warpage that at least partially corrects the warpage in the sensor.

In accordance with some embodiments, the warpage of the sensor has a curvature of a bow that is convex. In accordance with some embodiments, the warpage of the focal plane of the lens stack array has a curvature of a bow that is convex.

In accordance with many embodiments, the curvature of the warpage of the focal of the lens stack array is substantially equal to the curvature of the warpage of the sensor.

In accordance with some embodiments, the warpage of the lens stack array corrects the warpage of the sensor to provide back focal lengths for each of the lens stacks in the lens stack array that are substantially consistent.

In accordance with some embodiments, a method of manufacturing array cameras that correct for warpage in a sensor array with warpage in the focal plane of a lens stack is performed in the following manner. A first set of sensors for camera arrays are manufactured. Each of the sensors includes an array of pixels that is subdivided into of sub-arrays of pixels and each of the sub-arrays forms a focal plane. The warpage in each of the sensors manufactured is measured and used to generate warpage information. A lens stack array comprising a set of lens stacks where each of the lens stacks is associated with a focal plane formed by one of the sub-arrays of pixels in the sensor is designed based upon the warpage information. The designed lens stack array is configured to have a projection plane of images formed by the lens stack array that has a warpage that corrects the warpage in the sensor. A second set of sensors is manufactured and a lens stack arrays are manufactured in accordance with the design. The lens stack are then placed over the sensor to form and array camera module.

In accordance with some embodiments the lens stacks in each of the stack arrays is aligned with focal planes formed by the plurality of sub-arrays in each of the second set of sensors. In accordance with a number of embodiments, the warpage in the lens stack array design corrects the warpage of the first set of sensors to provide back focal lengths for each of the lens stacks in the lens stack array that are substantially consistent when placed over the second set of sensors.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** conceptually illustrates an array camera in accordance with an embodiment of the invention.

FIG. **2** illustrates an array camera module in accordance with an embodiment of the invention.

FIG. **3** illustrates an array camera module that employs a π filter in accordance with an embodiment of the invention.

FIG. **4** conceptually illustrates variations in focal length that can occur during the manufacture of an array camera module using a lens stack array and a sensor in accordance with embodiments of the invention.

FIG. **5** conceptually illustrates a convex warpage of a sensor of an array camera in accordance with embodiments of this invention.

FIG. **6** conceptually illustrates a concave warpage of a sensor of an array camera in accordance with embodiments of this invention.

FIG. **7** conceptually illustrates a lens stack array aligned over a sensor in accordance with an embodiment of this invention.

FIG. **8** conceptually illustrates a lens stack array that is designed with a projection plane that has a warpage that is substantially equal to the warpage in a warped sensor in accordance with an embodiment of this invention.

FIG. **9** illustrates a flow diagram of a process for manufacturing an array camera with a lens stack array that is designed with a warpage that is opposite the warpage in a warped sensor in accordance with an embodiment of this invention.

FIG. **10** illustrates a flow diagram of a process for mass manufacture of an array camera with a lens stack array that is designed with a warpage that is opposite the warpage in a warped or deformed sensor in accordance with an embodiment of this invention.

DETAILED DESCRIPTION

Turning now to the drawings, systems and methods for correcting warpage of a sensor of an array camera module by introducing warpage into a lens stack array in accordance with embodiments of the invention are illustrated. Processes for constructing array camera modules using lens stack arrays are described in U.S. Patent Publication No. 20011/0069189, entitled "Capturing and Processing of Images Using Monolithic Camera Array with Heterogeneous Imagers", Venkataraman et al. The disclosure of U.S. Patent Publication No. 20011/0069189 is incorporated by reference herein in its entirety. The monolithic array camera modules illustrated in U.S. Patent Publication No. 20011/0069189 can be constructed from an optic array of lens stacks, also termed a 'lens stack array', where each lens stack in the array defines an optical channel, and where the lens stack array is associated with a monolithic imager array, or 'sensor', including a plurality of focal planes corresponding to the optical channels in the lens stack array. Each focal plane can include a plurality of rows of pixels that also forms a plurality of columns of pixels, and each focal plane may be contained within a region of the imager array that does not contain pixels from another focal plane. An image may be formed on each focal plane by a respective lens stack. The combination of a lens stack array and a sensor can be understood to be an 'array camera module' and the combination of an individual lens stack and its corresponding focal plane within the sensor can be understood to be a 'camera.' Ideally, the lens stack array of an array camera is constructed so that each lens stack within it has the same focal length. However, the large number of tolerances involved in the manufacture of a lens stack array can result in the different lens stacks having varying focal lengths. The combination of all the manufacturing process variations typically results in a deviation of the actual ("first order") lens parameters—such as focal length—from the nominal prescription. As a result, each lens stack can have a different axial optimum image location. And consequently, since the sensor is monolithic, it typically cannot be placed a distance that corresponds with the focal length of each camera within an array camera module. There are a variety of processes in the manufacturing of conventional camera modules that can be utilized to align a lens stack array with a sensor to achieve acceptable imaging performance including active alignment processes and passive alignment processes.

One particular problem that arises during manufacture is that the lens stack array and/or the sensor may not be sufficiently flat when the components are combined into an array camera module. If either the lens stack array (or more particularly, the projection plane of the images projected from the lens stack) and/or the sensor are warped, the individual lens stacks may be misaligned with the desired focal planes when the lens stack array is affixed to the sensor causing varying focusing problems to arise. The sensor may be warped due to many factors, including, but not limited to, mismatch issues of the Coefficient of Thermal Expansion (CTE) of material of the sensor and of the Printed Circuit Board (PCB) during the attachment process in which the components are subjects to elevated curing temperatures. The lens stack array (or more particularly, the projection plane of the images projected from the lens stack) may be warped due to factors including, but not limited, manufacturing defects in the lens stack arrays and the stress induced by placement of the lens stack into a holder over the sensor. Although much of the discussion that follows refers to sensor warpage, the techniques described herein can be equally applied to correct any form of sensor deformation as appropriate to the requirements of specific manufacturing processes in accordance with embodiments of the invention.

The warpage of the lens stack array and/or the sensor may cause the distance and/or angle between the individual lens stacks and individual pixel arrays in the sensor to vary. This variation in distance and/or angle may cause a back focal length variation of the individual lens in the lens array over the focal planes on the sensor array of the array camera that is referred to as warpage of the projection plane of the lens stack where the projection plane is the plane in which the images are focused. Typically, the curvature sign of the bow of the warpage of the sensor is convex while the curvature sign of the bow of the warpage of the projection plane of the lens stack array may vary between convex and concave. Commonly, the only way to minimize back focal length variations is to minimize the warpage in between the projection plane of the lens stack and the sensor prior to alignment.

In accordance with some embodiments of this invention, the variations in the back focal lengths of the individual lens stacks in the lens stack array are reduced by matching the warpage of the sensor and the warpage in the projection plane of lens stack array such that the warpage in the projection plane of the lens stack array corrects for the warpage of the sensor. In accordance with some embodiments, the warpage may be corrected by forming the components such that the curvature sign of the bows for each component are substantially equal to one another. In accordance with some other embodiments, the warpage in the sensor may be corrected by varying the BFL of individual lens stacks in the lens stack array such that the curvature sign of the warpage of the projection plane is substantially equal to the curvature sign of the warpage of the sensor. The equality of the curvature signs of the deformation in the sensor and the projection plane of the lens stacks results in a defocusing pattern in the array camera that is substantially free of the bow. The variation in the resulting Back Focal Length (BFL) pattern of the array camera module is decreased relative to an array camera module manufactured using a planar lens stack array (i.e. a lens stack array manufactured to minimize warpage).

In accordance with some embodiments of the invention, the process for manufacturing an array camera module includes manufacturing and/or packaging a sensor without enforcing a flatness requirement. The warpage of the manufactured sensor can be measured to determine warpage information for the sensor. The warpage information for the sensor can be used to design a lens stack array with a warpage in the projection plane that corrects for the warpage in the sensor. In accordance with some embodiments, the warpage in the sensor is corrected by having a warpage in the lens stack array that has a bow curvature sign that is substantially equal to the bow curvature sign of the manufactured sensor array. In accordance with some other embodiments, the warpage in the sensor may be corrected by varying the BFL of individual lens stacks in the lens stack array such that the curvature sign of the warpage of the focal plane is substantially equal to the curvature sign of the warpage of the sensor. Conventional alignment and assembly processes can then be used to align the lens stack relative to the sensor and form an array camera module.

A process for manufacturing individual lens array stacks for each sensor array would costly and time consuming. Furthermore, while the magnitude of warpage observed in the sensor may be significant. For example the warpage may be as much as 25 μm. However, the variation of the warpage between sensors arrays manufactured in the same manufacturing lot is typically less than 5 μm and is more typically on the order of 3 μm. Thus, a process for matching the warpage of a lot of produced lens stack arrays to warpage in a lot of manufactured sensors arrays may be performed in in accordance with embodiments of this invention to reduce the BFL-variation in mass produced array camera modules. In some embodiments of this invention, the process includes manufacturing a group of sensors in an array using a standard process without enforcing flatness requirements. The warpage of each of the produced sensors in the group are then measured to generate warpage information. In accordance with some embodiments the warpage information may include an average bow curvature sign of the group of sensors. The warpage information of the group of sensors is then used to design a lens stack arrays with warpage of the array image surface that corrects for the warpage in sensors. In accordance with some embodiments, the lens stack array design has a bow curvature sign that is substantially equal to the bow curvature sign of the warpage in the group of sensors. Lens stack arrays can then be manufactured in accordance with the design and additional sensors can be manufactured in accordance with the process used to manufacture the initial group of sensors that formed the basis of the lens stack array design. Conventional alignment and assembly processes can then be used to form array camera modules from the lens stack arrays and sensors. The resulting array camera modules can have reduced BFL-variation relative to array camera modules manufactured without modifying the design of the lens stack arrays based upon the measured warpage of the initial group of sensors. In many instances, designing the lens stack array considering measured sensor warpage can increase array camera module yield and provide reductions in manufacturing costs.

Alignment of sensors and lens stack arrays may be performed using active/or passive alignment. In the context of the manufacture of camera systems, the term active alignment typically refers to a process for aligning an optical component or element (e.g. a lens stack array) with an image receiving component or element (e.g. a monolithic sensor) to achieve a final desirable spatial arrangement by evaluating the efficacy of the image receiving component's ability to capture and record images as a function of the spatial relationship between the optical component and the image receiving component, and using this evaluation information to assist in the alignment process. Processes for actively aligning a lens stack array with an array of focal planes are described in U.S. Patent Publication No. 2014/0002674, entitled "Systems and Methods for Manufacturing Camera Modules Using Active Alignment of Lens Stack Arrays and Sensors", Duparre et al. The disclosure of U.S. Patent Application Publication No. 2014/0002674 is incorporated by reference herein in its entirety.

Ideally, when manufacturing camera modules in bulk, each camera module would be individually assembled using a rigorous assembly process, such as an active alignment process, to provide a quality configuration. However, performing such processes in bulk may be costly and time-consuming. An alternative to the use of an active alignment process to manufacture camera modules is the use of a passive alignment process. The term passive alignment typically refers to aligning an optical system with an imaging system to achieve a final desirable spatial arrangement using predetermined configuration parameters (e.g., the spacing between the lens stack array and the sensor is predetermined). Processes for utilizing alignment information obtained during active alignment of one or more representative lens stack arrays and sensors to form array camera modules to manufacture array camera modules using passive alignment processes are disclosed in U.S. patent application Ser. No. 14/195,675 entitled "Passive Alignment of Array Camera Modules Constructed from Lens Stack Arrays and Sensors Based Upon Alignment Information Obtained During Manufacture of Array Camera Modules Using an Active Alignment Process" to Duparre et al. The disclosure of U.S. patent application Ser. No. 14/195,675 is incorporated by reference herein in its entirety.

Processes for aligning lens stack arrays with sensors in accordance with many embodiments of the invention involve aligning the lens stack arrays with respect to sensors so as to enhance the resulting array camera module's ability to produce high-resolution images using super-resolution processes. Super-resolution refers to the process of synthesizing a plurality of low-resolution images of a particular scene—each image providing a sub-pixel shifted view of that scene (i.e. the object space sampled by the pixels is shifted relative to the other images captured by the array camera)—to derive a corresponding high-resolution image. Essentially, in a super-resolution process, sampling diversity between the low resolution images of a scene captured by an array camera module is utilized to synthesize one or more high resolution images of the scene. Thus, an array camera can capture and record a plurality of low-resolution images, and employ a super-resolution algorithm to generate a high-resolution image. Super-resolution processes that can be used to synthesize high resolution images from a plurality of low resolution images of a scene are described in U.S. Patent Publication 2012/014205 entitled "System and Methods for Synthesizing High Resolution Images Using Super-Resolution Processes" published Jun. 14, 2012, the disclosure of which is incorporated by reference herein in its entirety.

The extent to which super-resolution processing can be utilized to obtain an increase in resolution of an image synthesized from a plurality of low resolution images can depend on the sampling diversity and sharpness of the images. Importantly, the sampling diversity of the captured low resolution images is partly a function of the spatial relationship between the lens stack array and the sensor. Thus, many embodiments of the invention further align the lens stack array with the array of focal planes to enhance the sampling diversity within the corresponding array camera module by discovering and implementing a spatial relationship between the lens stack array and the sensor that enables this result.

Array cameras and systems and methods for correcting warpage of a sensor of an array camera module by manufacturing lens stack arrays that include warpages that at least partially corrects for the warpage in the sensor in accordance with embodiments of the invention are discussed further below.

Array Camera Architectures

A variety of architectures can be utilized to construct an array camera using one or more array camera modules and a processor, including (but not limited to) the array camera architectures disclosed in U.S. Application Publication 2011/0069189. A representative array camera architecture incorporating an array camera module incorporating a warped sensor and a lens stack array incorporating warpage that at least partially corrects for the warpage in the sensor and a processor is illustrated in FIG. **1**. The array camera **100** includes an array camera module **110**, which is connected to an image processing pipeline module **120** and to a controller **130**. In the illustrated embodiment, the image processing pipeline and the controller **130** are implemented using a processor. In various embodiments, the image processing pipeline module **120** is hardware, firmware, software, or a combination for processing the images received from the array camera module **110**. The image processing pipeline module **120** is capable of processing multiple images captured by multiple focal planes in the camera module and can produce a synthesized higher resolution image. In a number of embodiments, the image processing pipeline module **120** provides the synthesized image data via an output **122**.

In many embodiments, the controller **130** is hardware, software, firmware, or a combination thereof for controlling various operational parameters of the array camera module **110**. The controller **130** receives inputs **132** from a user or other external components and sends operation signals to control the array camera module **110**. The controller can also send information to the image processing pipeline module **120** to assist processing of the images captured by the focal planes in the array camera module **110**.

Although specific array camera architecture is illustrated in FIG. **1**, camera modules incorporating a warped sensor and a lens stack array incorporating warpage that at least partially corrects for the warpage in the sensor in accordance with embodiments of the invention can be utilized in any of a variety of array camera architectures. Camera modules that can be utilized in array cameras and processes for manufacturing array camera modules in accordance with embodiments of the invention are discussed further below.

Array Camera Modules

An array camera module may be formed by aligning a lens stack array and an imager array. Each lens stack in the lens stack array can include an aperture that defines a separate optical channel. The lens stack array may be mounted to an imager array that includes a focal plane for each of the optical channels, where each focal plane includes an array of pixels or sensor elements configured to capture an image. When the lens stack array and the imager array are combined with sufficient precision, the array camera module can be utilized to capture image data from multiple views of a scene that can be read out to a processor for further processing, e.g., to synthesize a high resolution image using super-resolution processing.

An exploded view of an array camera module formed by combining a lens stack array with a monolithic sensor including an array of focal planes in accordance with an embodiment of the invention is illustrated in FIG. **2**. The array camera module **200** includes a lens stack array **210** and a sensor **230** that includes an array of focal planes **240**. The lens stack array **210** includes an array of lens stacks **220**. Each lens stack creates an optical channel that resolves an image on the focal planes **240** on the sensor. Each of the lens stacks may be of a different type. For example, the optical channels may be used to capture images at different portions of the spectrum and the lens stack in each optical channel may be specifically optimized for the portion of the spectrum imaged by the focal plane associated with the optical channel. More specifically, an array camera module may be patterned with "π filter groups." The term π filter groups refers to a pattern of color filters applied to the lens stack array of a camera module and processes for patterning array cameras with π filter groups are described in U.S. Patent Publication 2013/0293228, entitled "Camera Modules Patterned with π Filter Groups", Venkataraman et al. The disclosure relevant to π filter groups in U.S. Patent Publication 2013/0293228 is incorporated by reference herein in its entirety. FIG. **3** illustrates a single **7** filter group, wherein 5 lenses are configured to receive green light, 2 lenses are configured to receive red light, and 2 lenses are configured to receive blue light. The lens stacks may further have one or multiple separate optical elements axially arranged with respect to each other.

A lens stack array may employ wafer level optics (WLO) technology. WLO is a technology that encompasses a number of processes, including, for example, molding of lens arrays on glass wafers, stacking of those wafers (including wafers having lenses replicated on either side of the substrate) with appropriate spacers, followed by packaging of the optics directly with the imager into a monolithic integrated module.

The WLO procedure may involve, among other procedures, using a diamond-turned mold to create each plastic lens element on a glass substrate. More specifically, the process chain in WLO generally includes producing a diamond turned lens master (both on an individual and array level), then producing a negative mould for replication of that master (also called a stamp or tool), and then finally forming a polymer replica on a glass substrate, which has been structured with appropriate supporting optical elements, such as, for example, apertures (transparent openings in light blocking material layers), and filters.

Although the construction of lens stack arrays using specific WLO processes is discussed above, any of a variety of techniques can be used to construct lens stack arrays, for instance those involving precision glass molding, polymer injection molding or wafer level polymer monolithic lens processes. Issues related to variation in back focal length of the lens stacks within lens stack arrays are discussed below.

Back Focal Plane Alignment

An array camera module is typically intended to be constructed in such a way that each focal plane (i.e. an array of pixels configured to capture an image formed on the focal plane by a corresponding lens stack) is positioned at the focal distance of each lens stack that forms an optical channel. However, manufacturing variations can result in the lens stack in each optical channel varying from its prescription, and in many instances, these variations can result in each lens stack within a lens stack array having a different focal length. For example, parameters that may vary amongst individual lens stacks in a lens stack array because of manufacturing variations include, but are not limited to: the radius of curvature in individual lenses, the conic, higher order aspheric coefficient, refractive index, thickness of the base layer, and/or overall lens height. As one of ordinary skill in the art would appreciate, any number of lens prescriptions may be used to characterize the lens fabrication process, and the respective tolerances may involve departures from these prescriptions in any number of ways, each of which may impact the back focal length. Due to the monolithic nature of the sensor, the spatial relationship of the focal planes (with respect to the lens stacks) cannot be individually customized to accommodate this variability.

The variations in focal length that can occur in a conventional lens stack array are conceptually illustrated in FIG. **4**. The array camera module **400** includes a lens stack array **402** in which lens stacks **404** focus light on the focal planes **406** of sensor **408**. As is illustrated, variance between the actually fabricated lens stack and its original prescription can result in the lens stack having a focal length that varies slightly from its prescription and consequently an image distance that does not correspond with the distance between the lens stack array and the sensor. Accordingly, the images formed on the focal planes of the sensor can be out of focus. In addition, other manufacturing tolerances associated with the assembly of the array camera module including (but not limited to) variations in spacer thickness and alignment of the lens stack array relative to the sensor can impact all of the optical channels. Therefore, as discussed in U.S. Patent Publication 2014/0002674, active alignment processes may be incorporated in the manufacture of array camera modules to mitigate this effect.

One cause of variations in the focal lengths in a lens stack array is warpage of the lens stack array and/or sensor. A side view of a sensor showing a convex warpage of a sensor in accordance with an embodiment of the invention is shown in FIG. **5**. Although warpage is discussed with reference to the sensor, the discussion equally applies to a lens stack array. In FIG. **5**, sensor **500** has warpage causing the sensor **500** to have a convex bow. Typically stress induced during the packaging of a sensor, e.g. mounting onto a PCB, leads to a convex bow in a sensor such as sensor **500**. By convex, it is understood that convex describes the surface **505** of the sensor **500** that includes the pixel surface bowing outwards from sensor **500** (i.e. in a direction toward the lens stack array to which the sensor will be aligned) with respect to the expected plane **510** of the surface. The warpage may be caused by factors including (but not limited to) CTE mismatches between the material of the sensor and PCB material. For example a sensor generally includes a large amount of silicon and the PCB is made of a material such as, FR4, that has a much larger CTE than silicon Thus, elevated curing temperatures during bare die and/or CSP attachment process(es) as well as actual board manufacturing processes may introduce the convex warpage into the sensor **500**.

A sensor having a concave bow in accordance with embodiments of this invention is shown in FIG. **6**. One skilled in the art will recognize that a lens stack array may also have a concave bow and the following discussion also applies to a lens stack array. Sensor **600** has concave bow. One skilled in the art will recognize that a concave bow in a sensor typically does not occur. By concave, it is understood that concave describes the surface **605** of the sensor **600** that includes a pixel surface **605** bowing inwards towards sensor **500** (i.e. in a direction away from the lens stack to which the sensor is aligned.

The lens stack array may also have warpage. Warpage in the lens stack array and/or other factors may cause warpage in the projection plane of the images from lens stack array. The BFL-pattern of the warpage in the projection plane of the lens stack array may vary between concave and convex. It is understood that concave and convex describe the shape of the warpage of the lens stack array with respect to the expected plane of the surface of the pixels in the sensor array as described above with reference to the sensor. In a conventional array camera module, the warpage of the lens stack array may be caused by the lens stack array being introduced into a hold over the sensor and/or a variation of the focal planes from the focal planes of a flat lens stack array.

In accordance with some embodiments of this invention, the effective variations in the back focal lengths of the individual lens in the lens stack array causing warpage in the projection plane of the lens stack array are reduced by matching the warpage of the sensor and the warpage of the projection plane of lens stack array such that the curvature signs of the bows for each warpage are substantially equal to one another. The equality of the shape of the deformation in the sensor and the projection plane of the images formed by the lens stack array results in an effective defocusing pattern in the array camera that is substantially free of the bow. The resulting effective variation in the Back Focal Length (BFL) pattern of the array camera module is decreased. The placement of the lens stack array over the sensor in accordance with embodiments of the invention is shown in FIG. **7**. In FIG. **7**, lens stack array **710** is positioned over sensor **720** such that each individual lens stack **711** is aligned with an individual focal plane of pixels **721** to form array camera module **700**.

The warpage of each of the lens stack array and sensor of an array camera module in accordance with an embodiment of the invention is shown in FIG. **8**. In FIG. **8**, sensor **720** has a curvature that is convex in that the warpage causes a pixel surface of sensor **720** to bow outward from sensor **720** toward the lens stack array with respect to the expected plane of the surface of pixels in the sensor **720**. Lens stack array **710** has a curvature that is convex in that the warpage of lens stack array **710** causes lens stack array **710** to bow outward from sensor (i.e. away from the sensor) with respect to an expected plane of the surface of pixels in the sensor. Thus, when lens stack array **710** is placed over sensor **720** the warpage of lens stack **710** is the substantially equal to the warpage of sensor **720**. Thus, the axial alignment between the individual lens and sensors is maintained. More particularly, the equality in the warpage of each component causes the warpage of the projection plane of the images formed by the lens stack to be substantially equal to the warpage of the sensors. Thus, the projected images from the lens stack array have the same focal distance with respect to the sensor. In accordance with other embodiments, the warpage of the projection plane of images other manners including, but not limited to, adjusting the optics in one or more lens stacks in the lens stack array. One skilled in the art will recognize that either component or both components may have different curvatures signs of the bows, the only requirement being that the warpage of the lens stack array corrects for the warpage of the sensor **720** in accordance with some embodiments of this invention.

Processes for manufacturing an array camera module that includes a lens stack array incorporating warpage that at least partially corrects warpage in a sensor in accordance with an embodiment of the invention is illustrate in FIG. **9**. Process **900** is a process for manufacturing a single array camera module that includes a lens stack array that has warpage that at least partially corrects warpage in a sensor in accordance with an embodiment of the invention. In process **900**, a sensor is manufactured using conventional processes (**905**). In accordance with some embodiments, the flatness requirements of the sensor are relaxed during the manufacture process of the sensor which includes the mounting of the sensor to a PCB. The warpage of the sensor is then measured (**910**). In accordance with some embodiments, the measurements include a curvature sign of a bow. In accordance with some embodiments, the measurements are performed using testing equipment and the results are provided to processing system, such as a computer. In some embodiments, the results of the measurement are stored to a memory for later use.

The measurements of the warpage are then used to determine the warpage needed in the projection plane of the images formed by the lens stack array. The required warpage needed is then used to generate a design specification for a lens stack array that provides the desired warpage in the projection plane of the images formed by the lens stack array (**915**). The design specification is a specification that results in a lens stack array that provides a projection plane that has a warpage that corrects for the warpage in the sensor. In accordance with some embodiments, the correction causes the projection plane of the lens stack array to have of curvature sign of a bow that is the same as that the curvature signs of the sensor. The design specification can be generated by a computer system that receives the measurements from the testing equipment and applies design algorithms to the measurement results to determine the proper design specification based upon the desired warpage of the projection plane.

The design specification is then used to generate a lens stack array to match the measured sensor (**920**). Conventional processes such as, but not limited to WLO techniques can be used to manufacture the lens stack array in accordance with embodiments of the invention. The manufactured lens stack can then be placed over (**925**) and aligned (**930**) with the sensor using conventional processes to form an array camera module.

Although specific embodiments of a process for manufacturing an array camera module in accordance with an embodiment of this invention are described above with reference to FIG. **9**, other processes may be used to manufacture an array camera module in accordance with other embodiments of this invention.

The making of a specific lens stack array for a specific sensor may be too expensive and too time intensive for mass production of array camera modules. Thus, alternative process for manufacturing array camera modules may use lens stack modules that are configured to correct average warpage of manufactured sensors and/or warpages that are replicated across multiple sensors by the sensor manufacturing process. A flow chart of a process for the mass manufacture of array camera modules having lens stack arrays that are designed to correct the average warpage of manufactured sensors in accordance with an embodiment of this invention is shown in FIG. **10**. Process **1000** includes manufacturing a test group of sensors (**1005**). In accordance with some embodiments, the flatness requirements of the sensors are relaxed during the manufacturing and/or packaging process of the sensors. The warpage of each sensor in the test group of sensors can then be measured (**1010**). In accordance with some embodiments, the measurements include a determination of the curvature of each sensor. In accordance with many embodiments, the measurements are performed using testing equipment and the results are provided to a processing system, such as a computer. In several embodiments, the results of the measurement are stored to a memory for later use.

The measurements of the warpage of the test group of sensors are then used to determine one or more design specifications for a lens stack array(s) (**1015**). The design specification is a specification that results in a lens stack array that provides a projection plane of the images formed by the lens having a warpage of the projection plane of the images formed by the lens stack array (either by respective mechanical deformation of the lens stack array itself, or by incorporation of the respective BFL-variation) that at least partially corrects for the average warpage in the test group of sensors. In accordance with some embodiments, the warpage of the projection plane of the lens stack array is achieved by mechanical deformation of the lens stack array itself. In accordance with some other embodiments, the warpage of the projection plane of the lens stack is achieved by BFL-variation of the optics in the individual lens stacks in the array. In accordance with some embodiments, the correction causes the projection plane of the lens stack array to have of a curvature that is identical to the curvature observed in the initial group of sensors. The design specification can be generated by a computer system that receives the measurements from the testing equipment and applies design algorithms to the measurement results to determine the proper design specification for the lens stack array that corrects for the warpage in the sensor.

Sensors can be manufactured in accordance with the previous processes used to manufacture the test group of sensors (**1020**). The design specification can then be used to generate lens stack arrays to match the manufactured sensors (**1025**). Conventional processes such as, but not limited to WLO techniques can be used to manufacture the lens stack array in accordance with embodiments of the invention. The manufactured lens stack can then be placed over (**1030**) and aligned with the sensor (**1035**) using conventional processes.

Although specific embodiments of a process for manufacturing array camera modules in accordance with an embodiment of this invention are described above with reference to FIG. **10**, other processes may be used to manufacture an array camera module in accordance with other embodiments of this invention.

Although the present invention has been described in certain specific aspects, many additional modifications and variations would be apparent to those skilled in the art. It is therefore to be understood that the present invention may be practiced otherwise than specifically described. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

What is claimed is:

1. An array camera comprising:

an array camera module including:

a sensor including an array of pixels that is subdivided into a plurality of sub-arrays of pixels, where each of the plurality of sub-arrays forms a focal plane; and

a lens stack array comprising a plurality of lens stacks wherein each of the plurality of lens stacks includes an aperture and forms an image on a focal plane formed by one of the plurality of sub-array of pixels on the sensor;

wherein the surface of the sensor on which images are formed by the lens stack array includes a warpage;

wherein a projection plane of images formed by the lens stack array incorporates a warpage that at least partially corrects the warpage in the sensor.

2. The array camera of claim **1** wherein the warpage of the sensor has a curvature of a bow that is convex.

3. The array camera of **2** wherein the warpage of the focal plane of the lens stack array has a curvature of a bow that is convex.

4. The array camera of **1** wherein the curvature of the warpage of the focal of the lens stack array is substantially equal to the curvature of the warpage of the sensor.

5. The array camera of claim **1** wherein the warpage of the lens stack array corrects the warpage of the sensor to provide back focal lengths for each of the plurality lens stacks in the lens stack array that are substantially consistent.

6. A method for manufacturing an array camera module comprising:

manufacturing a sensor including an array of pixels that is subdivided into a plurality of sub-arrays of pixels wherein each of the plurality of sub-arrays forms a focal plane;

measuring a warpage of the sensor to generate warpage information;

generating a design for a lens stack array comprising a plurality of lens stacks wherein each of the plurality of lens stacks is associated with a focal plane formed by one of the plurality of sub-array of pixels in the sensor and wherein the lens stack array is configured to have a projection plane of images formed by the lens stack array that has a warpage that corrects the warpage in the sensor based upon the warpage information for the sensor;

manufacturing the lens stack array in accordance with the generated design; and

placing the lens stack array over the sensor to form an array camera module.

7. The method of claim **6** further comprising:

aligning the lens stacks in the lens stack array with focal planes formed by the plurality of sub-arrays in the sensor.

8. The method of claim **6** wherein the warpage of the lens stack array corrects the warpage of the sensor to provide back focal lengths for each of the plurality of lens stacks in the lens stack array that are substantially consistent.

9. The method of claim **6** wherein the warpage of the sensor has a curvature of a bow that convex.

10. The method of **9** wherein the warpage of the projection plane of lens stack array has a curvature of a bow that is convex.

11. The method of **9** wherein the curvature of the warpage of the projection plane of the lens stack array is substantially equal to the curvature of the warpage of the sensor.

12. The method of claim **6** wherein the flatness requirements for the sensor are relaxed during the manufacturing and packaging of the sensor.

13. A method for mass manufacturing an array camera module comprising:

manufacturing a first plurality of sensors wherein each of the plurality of sensors includes an array of pixels that is subdivided into a plurality of sub-arrays of pixels wherein each of the plurality of sub-arrays forms a focal plane;

measuring a warpage of each of the first plurality of sensors to generate warpage information;

generating a design for a lens stack array comprising a plurality of lens stacks wherein each of the plurality of lens stacks is associated with a focal plane formed by one of the plurality of sub-array of pixels in the sensor and wherein the lens stack array is configured to have a projection plane of images formed by the lens stack array that has a warpage that corrects the warpage in the sensor based upon the warpage information for the first plurality of sensor;

manufacturing a second plurality of sensors in accordance with a process used to manufacture the first plurality of sensors;

manufacturing a plurality of lens stack arrays in accordance with the generated design; and

placing a one of the lens stack arrays over one of the second plurality of sensors to form array camera modules.

14. The method of claim **13** further comprising:

aligning the lens stacks in each of the plurality of lens stack arrays with focal planes formed by the plurality of sub-arrays in each of the second plurality of sensors.

15. The method of claim **13** wherein the warpage in the lens stack array design corrects the warpage of the first plurality of sensors to provide back focal lengths for each of the plurality of lens stacks in the lens stack array that are substantially consistent when placed over the second plurality of sensors.

16. The method of claim **13** wherein the warpage of the first and second plurality of sensors has a curvature of a bow that convex.

17. The method of **16** wherein the warpage of the projection planes of the plurality of lens stack arrays have a curvature of a bow that is convex.

18. The method of **16** wherein the curvature of the warpage of the projection planes of the plurality of lens stack arrays is substantially equal to a curvature of bow of the warpage of the plurality of sensors.

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